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Evaluation indicators for urban ecological security based on ecological network analysis

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Abstract

The urban ecological infrastructure, mainly consist of urban landscape, provides the eco-services for the development of society and economy. The stability of landscape eco-system function is the necessary condition holding the status of urban ecological security. This article introduces the metapopulaiton capacity into the evaluation of ecological network stability, improves the calculation of the metapopulaiton capacity, and forms a new indicators system which combines the metapopulation capacity with some indicator used in the ecological network analysis to measure the urban ecological security. At last, indicators for urban ecological security based on ecological network analysis discussed above are established for Guangzhou.

*Keywords:*Ecological network analysis; metapopulation capacity; Guangzhou

1. Introduction

Modern cities are increasingly expanding with social and economical development. China's urbanization rate is increasing rapidly and stood at 45.68% in 2008, according to the urban environmental management and comprehensive annual report issued by the Ministry of Environmental Protection. Expansion of city areas and changes of land use pattern make the urban landscape fragmented increasingly. Urban ecological infrastructure, mainly consist of urban natural landscape, is the main provider of the eco-services for development of society and economy. The sharp change of structure and function of urban landscape has weakened the eco-services function provided by urban ecological infrastructure, and has threatened the urban ecological security and sustainable development. For keeping the security of urban ecological system, managers and scientists are always to seek for the suitable urban planning method to regulate and perfect the urban landscape structure and to protect the stability of the key ecosystem function. Ecological network analysis (ENA) can be used to evaluate the spatial planning's suitability to urban landscape eco-system, and to optimize the spatial planning through the scenario analysis. This method is also suitable for the evaluation of urban ecological security and urban planning.

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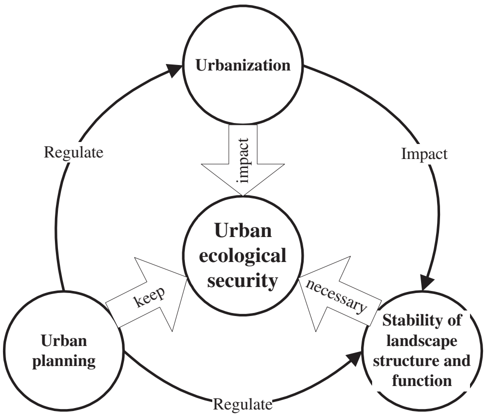

Figure1 the relationship among urbanization, urban planning and stability of landscape structure and function

Ecological security, proposed by the government of United States [1], does not have universally accepted definition now. Here, from the relationship between urban landscape ecological system and ecological security, the urban ecological security can be regarded as the status that the structure of the urban landscape is integrated and the function is stable to provide enough eco-services to support the development of the socio-economic system and further to maintain the urban sustainable development.

Ecological networks, derived from landscape architecture and planning of North America, refer to a set of ecosystems, which linked into a spatially coherent system through flows of organisms, and interacted with the landscape matrix in which it is embedded. The ENA is a method to analyze, evaluate, regulate and perfect the ecological network in order to hold the stability of the landscape ecosystem function.

From 1990s, ENA was used in regional and national scale to conserve natural resources or to manage protection zone [2-7]. The study contents included the basis concept of ecological network, the function of ecological network, the identification and structure of ecological network, and the evaluation and planning of ecological network etc. The methods that are used in the evaluation of ecological networks are mainly based on the landscape ecology and graph theory. Such as Zhang et al [8] analyzed ecological network of Xiamen Island (China) through landscape ecological indicators. Xiong [9] take indicators of network connection and accessibility in according with graph to measure the integrity of urban eco-network. Andreas [10] combined graph theory and network analysis to explore landscape or habitat connectivity. The methods based on the graph theory which simplify the complex landscape system into a network graph (digraph or undigraph) [11] is beneficial to visually measure the topology, connectivity and complex of the landscape network structure. Although, this simplicity, especially patches or habitats were abstracted nodes, results to some useful information lost. The method of landscape ecology establishes the relation between the landscape structure and function, and some of indicators could evaluate the ecological value of single patch and corridor, but there is less the synthetical description of the features of patches.

When introduced ENA to urban planning, Edward [12] thinks three principal analyses in the study should be followed: (1) patch content analysis, (2) corridor content analysis, and (3) network structure analysis. From the situation of the study now, there is much emphasis put on the network structure analysis. Indeed, the structure of ecological network in the urban area is very important for material circulation and energy flow among fragmentized patches. But from the viewpoint of ecological security, the eco-services that support the development of urban socio-economy is provided by the urban ecological infrastructure, composed mainly by urban natural landscape patches, so seeking for some methods that are able to integrate the patch influence into the network analysis is more valuable and important. Some methods involve metapopulaiton dynamic provide new ideas for the study.

The concept of metapopulation was proposed by Richad Levins [13] to describe a “population” consisting of many local populations in which a local population is a population consisting of individuals. Because of its application in landscape ecology and in conservation biology, there are many researchers about the theory and application [14-20]. According to the form of dealing with spatial relation of metapopulation, the models described the metapopulation dynamic can be divided into three types: Spatially implicit metapopulation model, SIM; Spatially explicit metapopulation model, SEM; Spatially realistic metapopulation model, SRM. Incidence function model (IFM), describing the spatially explicit metapopulation, which includes geometric information of landscape and can be use to directly simulate the real landscape [21], is the most advanced model. But the IFM is a linear markov model used in the single habitat, it is limited to be applied into the landscape ecological network. Hanski and Ovaskainen [22] turned to matrix notation to describe the system of equations giving the rates of change in the probability of the single patch being occupied, and defined the leading eigenvalue of the matrix as the metapopulation capacity of a fragmented landscape to measure the bearing capacity of landscape patches for some species. Subsequently, they discussed the global and local assessment of metapopulation capacity [23]. Otso [24] explored the individual habitat fragment contribution to metapopulation persistence based on the metapopulation capacity. Cang [25] analyzed the interaction of carrying capacity, population equilibrium, and environment's maximal load. In the study about the rapid evaluation method of metapopulation persistence, Michael [26] improved the calculation of metapopulation capacity in order to apply it to highly variegated landscapes. Although there are many researchers think that metapopulation capacity is suitable for the study on the landscape ecology, there is less discussions on the ecological networks and in the scale of cities.

So this article introduces metapopulation capacity into the ENA in the urban landscape, try to improved ENA and make it applicable to evaluate the urban ecological security. At last, indicators for urban ecological security based on ecological network analysis discussed above are to establish for Guangzhou city.

2. Evaluation indicators

This section we will firstly discuss the model applicability used in the urban landscape and habitats of metapopulation (section2.1), then the calculation of metapopulaiton capacity and the transformation will be described (section 2.2), last the metapopulation capacity and the indicator of ENA will be combined to form the comprehensive indicators measuring the urban ecological security(section 2.3).

2.1. The discussion of applicability

Because there is no metapopulaiton dynamic model applied in the scale of city, it is necessary to discuss the similarity with the urban landscape and habitats of metapopulation. Hanski et al [27] defined a typical metapopulation as a system satisfying the following four standards: (i) a survivable niche exists in the form of scattering patches; (ii) the largest regional metapopulation is faced with the risk of extinction as the smallest one; (iii) patches are not too separated to be recolonized; (iv) all regional metapopulations are not likely to synchronize completely. (i)Because of the artificial disturbance, the area of natural landscape patches has sharply reduced in the urban landscape, exist large patches have yet been broke up into several small patches connected by natural or artificial corridors. The species of urban area is survival in scattering patches, and depend on the corridors or other form to migrate among the patches, seek for the optimal habitat or avoid interference, in order to keep the species persistence. (ii)Because of the uncertainty of natural condition and human activity, the change of each patch and connected corridors is uncertain, it could impact the capacity of the patch to the local population. The risk of extinction of local population survival in each patch is uncertain, namely the largest metapopulation might face with the same risk of extinction as the smaller one. (iii)For protecting the ecological flows among the fragmented landscape ecosystem in the city, corridors are built up to connect each patch, these corridors could guarantee that patches are not too separated to be recolonized. (iv) In the urban area, some patches are artificial or disturbed severely by the human such as farmland and public garden, the survival condition of each patch for some species is different in different period. The species had to migrate one to another to keep the population persistence according to resource condition of patches. When there are many patches in which the resources condition of each patch is different in different period, the incidence of all regional metapopulation synchronizing completely is very little.

2.2. Calculation and transformation of metapopulation capacity

The traditional calculation of metapopulation capacity described by Hanski and Ovaskainen [22] is the leading eigenvalue of matrix M which is a patch-by-patch matrix consisting of elements $m_{ij}=\exp(-\alpha d_{ij})A_iA_j$ for $i \neq j$ and m=0. Where A_i is the area of path i, α_{ij} is the distance between patches i and j, $1/\alpha$ is the average migration distance. In the application, some researchers [26] think $w=\exp(-\alpha d_{ij})$ is the probability of successful movement at distance d, and distinguish the matrix among patches into good matrix and poor matrix for a species, and the migration ability (refer to the movement distance) is better in good matrix.

There we will improve it with more detail information. In landscape ecology, the least-cost distance might express the relative accessibility of some path from the source to certain point in space. So the cumulative value $D_i \times R_i$ could instead the real distance d_{ij}.

If we assume some species' migration ability (the longest distance this species can migration) in the landscape is changed with the habitat conditions. With the differentiation with the optimum habitat increasing, the work a species need to spend in the process of spread will increases, and the species' migration ability will decrease. According to the impacts to species' migration in all kinds of landscape type, we could give different value of resistance.

Table 1 The classification of relative resistance

Relative value of resistance	Impact	Explain
1	Non-resistance	The landscape factor is the same with the habitat
2,3	Low resistance	There is a little resistance, the landscape factor is similar with the habitat, such as forest and shrub
4,5	Middle resistance	The landscape factor is the vegetation form by artificial disturbance, such as Savanna and grassland
6,7	High resistance	The zone of artificial disturbance obviously, such as cropland
8,9	Very high resistance	Urban main highways or water which interested species is difficult to through
10	Top resistance	Urban constructed area of large, high-density or highway or cliffs that interested species is difficult to through

Note: the impact of the matrix mainly depends on the special species' attribute.

At the same time, the area of path i could instead by the viable area, because the edge effect of the irregular habitat for a single species is always disadvantageous, we can use round area instead the real area in order to avoid this impact.

So the elements contained in the matrix M can be changed into

$$m_{ij} = \exp\left(-\alpha \sum_{x=1}^{n} D_{xy} R_x\right) A_i A_j \qquad (i \neq j \text{ and } m_{ij} = 0) \qquad (1)$$

Where D_{xy} is the spatial distance from the source y to some point in space when species passes the landscape type i; R_x is the movement resistance of the landscape x to some species. A_i is the viable area of path i. The leading eigenvalue λ_m is the metapopulation capacity in the special landscape.

In metapopulation model, the impact from other patches to interested patch is considered as an independent process. In practice, migration paths have the influence to each other in ecological network. But this model could not reflect the information that diversity and cycling among patches are good for stability of the network. For example, in metapopulation model, the impact from patch 1 and patch 3 is the same for patch 2 in picture 1(a) and 1(b), the network cycling is overlooked, but obviously, landscape 1(a) is more stable than landscape 1(b). The metapopulation capacity could combine the structure information and biological information, but could not reflect the integrated state of ecological networks.

(a) (b)

Figure2 The impact to patch 2 of different landscape network circulation

2.3. The combination of metapopulation capacity and the indicator from ENA

In the classical ENA, whose object of study is the ecological network based on the food web, the ecological network circulation (ENCI) is used to measure the intensity of circulation paths in the network. And this indicator reflects the smooth and diversity of the ecological process, and the ability of material migration, feedback and self-organization. Zang [11] has introduced it into the ENA of landscape to depict the circulation of landscape network. But she thought the ecological network circulation can not depict the network comprehensively when the network is not the strong graph [28]. So she developed the indicator of ecological network connection (ENCO) to improve it.

Because ENCI and ENCO can well describe the circulation and connection of the ecological network, they could make up the insufficient of metapopulation capacity in the evaluation. The ENCI increase indicates the regional circulation is strengthened, the ecological diversity rise, and the network is active, but some patches might become isolated. The ENCO could make sure all the patches need to connect with each other. If there are nice ENCI and ENCO, patches location, area and ecological flows between neighbours are good enough to support the key population development, the stability of ecological network is guaranteed. So synthesize the metapopulation capacity, ENCO and ENCI, the comprehensive indicator to measure the stability of ecological network can be expressed as below:

$$FS = \lambda_M \times ENCI \times ENCO = \lambda_M \times \frac{\lambda_m}{N} \times \frac{n}{N} = \frac{n\lambda_m\lambda_M}{N^2} \qquad (2)$$

Where the FS is the stability of ecological network; λ_m is the largest eigenvalue of the adjacent matrix depicting the network; N is the number of nodes of the network; n is the number of node in the strongly connected components.

3. Case study

Guangzhou, capital of Guangdong Province, is one of Chinese main industrial centers, covering an area of 7,434 square kilometers, and with a population of over 6 millions. Guangzhou stands at the confluence of the East River, West River and North River, with its land sloping from north-east to south-west, and an alluvial plain in the south and south-west parts. It adjoins the South China Sea, and is crisscross with rivers and streams. It has south subtropical marine climate with an annual average temperature of 21.8 degree Celsius, rainfall of 1694 millimeters, and a frost-free period of 345 days. It's abundant in agricultural and aquatic resources. Due to the superior geographic and climatic conditions, plant species is very rich in Guangzhou, trees species of theaceae, fagaceae and lauraceae are dominant.

The metapopulaiton dynamic model simulates the colonization and exiction of a single species, so the metapopulaiton capacity get from this model is the carrying capacity to a single species. There the metapopulation capacity to a single species will stand for the carrying capacity to the eco-system, so we should choose the typical species as the interested species. The interested species could be plant or animal, whose metrapopulation capacity can be regarded as the indicator evaluating the stability of urban landscape ecological network. Two core principles for choosing interested species should be as following:

- The interested species should be located in the bottom of the food chain of eco-system. According to the ecology theory, the species situated in the bottom of food chain provide the food source for the advanced species, they are the fundament of the community persistence.
- The interested species must be the local species, and could represent the attribute of local biological resources. There the geological conditions is put much emphasis in metapopulaiton persistence, but the conditions of climate, water etc. are ignored, so we must choose the local species to avoid the other impact to the interested species.

On the basis of the current status of biological resources in Guangzhou, and the principals of the species choice, we choose the wild evergreen species of Fagaceae in Guangzhou as the interested species. The evaluated indicator system is listed below:

Table 2 the evaluated indicators in Guangzhou

Indicators	Description
N	The number of nodes of the ecological network
n	The number of node in the strongly connected components
λ_M	Metapopulation capacity
λ_m	The largest eigenvalue of the adjacent matrix depicting the network
ENCI	$ENCI = \frac{\lambda_m}{N}$
ENCO	$ENCO = \frac{n}{N}$
FS	$FS = \lambda_M \times ENCI \times ENCO = \lambda_M \times \frac{\lambda_m}{N} \times \frac{n}{N} = \frac{n\lambda_m\lambda_M}{N^2}$

4. Conclusion and Proposal

This paper uses metapopulaiton capacity to evaluate the stability of urban landscape eco-system. The metapopulation capacity could combine the network structure information and biological information to measure the function integrity of the special landscape, but, it ignores the impact of the network cycling. So the network circulation based on the graph theory is introduced to offset the disadvantage of metapopulation dynamic model. The indicator of ENCI and ENCO could reflect the circulation of the whole ecological network. It can weight the metapopulation capacity to form a comprehensive indicator to measure the stability of the urban ecological network and further the urban ecological security. But the indictor of metapopulaiton capacity focus on a single species, there we use the matapopulation capacity of a single species instead of the eco-system capacity of the landscape, so the selected species should be typical and representative. And the study of multi-species metapopulaiton capacity is needed and valuable to decrease the uncertainty of the evaluation. The combination of biological indicator and ecological network indicator is an innovation of this paper, but the form of combination is the weight simply, it need more research about the relation between indicators.

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